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A robust control of mobile inverted pendulum using single accelerometer

Hyunuk Ha, Sungmin Ryu, Jangmyung Lee (Dept. of Electrical engineering, Pusan National University, Korea)

(Tel : +82-51-510-1696; Fax : +82-51-514-1693)
(hhook@pusan.ac.kr, smryu@pusan.ac.kr, jmlee@pusan.ac.kr)

Abstract: This paper proposes a single accelerometer sensor control algorithm to mobile inverted pendulum(MIP), generally called 'Segway', and evaluates the performance of this system comparing to the conventional ones. The commercialized 'Prototype Segway-PT' is initially considered as a next-generation transport vehicle. However, this robot is operated by three gyroscopes and two accelerometers to control the posture and speed, and it requires the complex signal processing for fusing the two sets of data. As the result of this, the growth rate of market size of 'Segway' is slow because of its high price mainly. In this paper, the MIP is operated by a single accelerometer to simplify the control system to lower the price. Low pass filter is one of the good sensors to reducing the variation of an accelerometer, but it has time delay. This time delay disturbs real-time control. Like this, other various algorithms are used for this system, but each one has their own weak points. So this paper proposes a new accelerometer filtering method, median filter and EKF. Median filter is used to image processing to reject impulse elements like 'salt & pepper noise'. As the major performance evaluation parameter for the accelerometer, the high-frequency to low frequency ratio from FFT(Fast Fourier Transform) and PSD(Power Spectral Density) are used. Effectiveness of the proposed algorithms has been verified and demonstrated through the simulations using matlab and real experiments for a MIP.

Keywords: Segway, Mobile inverted pendulum, accelerometer, performance evaluation, filter

I. Introduction

The mobile inverted pendulum(MIP), generally called 'Segway' is invented by Dean Kamen in 2001 for commercial use[1]. At that time, 'Segway' is considered as next-generation transportation. Conventional transportation method by that time guaranteed the stability along the pitch direction by the position of the wheels which is placed at the front and the rear, but the wheels of the 'Segway' is placed by the side of the robot body[2]. The 'Segway-PT' use five gyroscopes and two tilt sensors to sensing the angle of robot body's slope. By the two kinds of sensor information, robot can real-time calculate the alternation of COG(Center Of Gravity), then moving from the combined information of the knob, which determine the direction, and the angle calculated as above sequences.

Commercialized 'Segway' use sensor fusion of multiple gyroscopes and tilt sensors, 'Segway' is relatively experience to be a next-generation transporter. The MIP is well researched for partial feedback linearization method[3] and iterative impulsive control[4], and so on. But these researches is biased to control algorithm fields, and this is initially assume that multiple sensor fusion algorithm. These factors make 'Segway' is lack of sociality, nevertheless it has a strong advantage like unnecessariness of a special skill like bicycle.

This paper proposed a new single accelerometer filtering algorithm to control MIP. Median filter, popularly used in image processing, and EKF(Extended Kalman filter) was used to reduce the fluctuation noise of the accelerometer signal.

This paper is consist of six-sections including introduction. In section 2, the shortcoming of LPF(Low Pass Filter) for the accelerometer, a time delay caused by time constant and lack of robustness, and theoretical back ground of signal processing of accelerometer, median filter and EKF as mentioned above, is stated. Section 3 shows the simulation and experimental results. Section 4 describes the performance evaluation by spectrum analysis using FFT(Fast Fourier Transform) and PSD(Power Spectral Density). In section 5, experimental environment and simulation tool, fda-tool(A filter design and analysis GUI tool) of provided by matlab, was described, and compare conventional block diagram of MIP and proposed one. In section 6, detail conclusion is described by quantitative analysis based on section 5, verified simulations and real experimental results.

II. Single accelerometer filtering algorithm

Conventional MIP control method is sensor fusion of multiple gyroscopes and tilt sensors for reliable angle information. Gyroscope is robust for the external disturbance by the structural characteristics. But generally, gyroscope has many demerits, 1. Truncation error caused by limited sampling period or limited bits for resolution of A/D converter. 2. Non-linearity of conversion factor by the temperature. 3. Feasible modeling error caused by G-sensitivity. 4. The gap of angular velocity information mean and 0(integrate infinitely and this unbiased information lead to accumulate of angle signal), generally called bias drift[3]. This gyroscope error signal is accumulated as time goes on. By this reasons, commercialized 'Segway' use sensor fusion algorithm to estimate angle. For another sensor, tilt sensor is weak for the external disturbances so if there exist disturbances over the fixed threshold, the robot operates as a hardware amplifier, so sometimes it's diverging. The most common filtering method for reducing this variation is LPF. But LPF has its own time delay caused by time constant, essentially exist during designing a LPF. This time delay makes MIP hard to real-time control, so LPF has some restrictions to apply for single accelerometer signal processing. Figure 1 illustrates the shortcoming of LPF for mobile inverted pendulum.

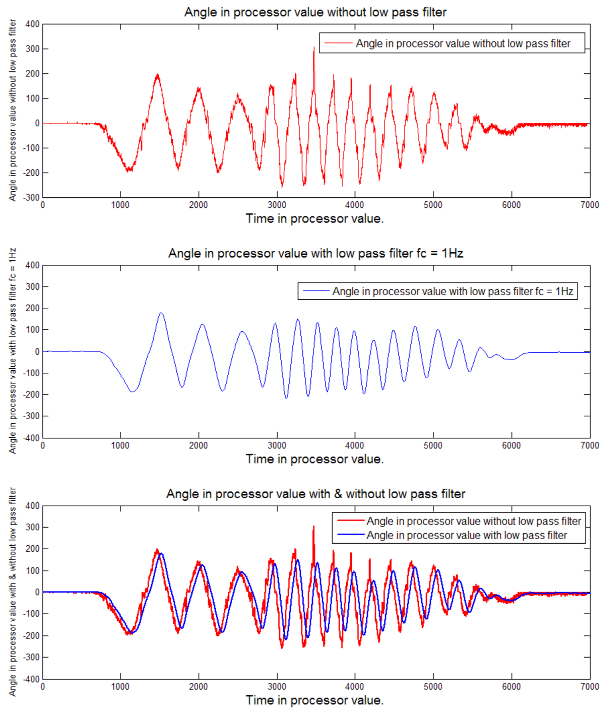

Fig. 1. Shortcoming of low pass filter for mobile inverted pendulum

Figure 1.a. shows the accelerometer signal without filter. It has many variations having high frequency. Figure 1.b. displays the accelerometer signal after 10^{th} order LPF. Figure 1.c. illustrates both signal stated above. After LPF signal doesn't have high frequency information but has time delay comparing with original signal. So LPF is not suitable for real-time controller like MIP.

This paper proposed a new real-time accelerometer noise & variation reduction algorithm, median filter and EKF, one of the most effective adaptive filter. The theoretical back ground of these two method is described next section.

2.1. Median filter

Median filter is well known as a most effective filter to removing AWGN widely distributed in frequency domain, especially removing 'salt & pepper noise' which has impulsive noise in image processing. The window of median filter can be adjusted as various formulations. But the accelerometer signal is real-time one dimensional signal, so set up a horizontal window. Median filter algorithm as stated above is simply realized as figure 2.

```
For cnt1=0,… N1          // N1 is variable window size
    For cnt2=cnt1+1,… N1 +1
        If  ( accelerometer[cnt1] > accelerometer [cnt2] )
            temporary value   =  accelerometer[cnt1];
            accelerometer[cnt1] =  accelerometer[cnt2];
            accelerometer[cnt2] =  temporary value;
        End if
    End for
End for
```

Fig. 2. Median filter algorithm

Figure 3 illustrates the results for median filter applied to single accelerometer.

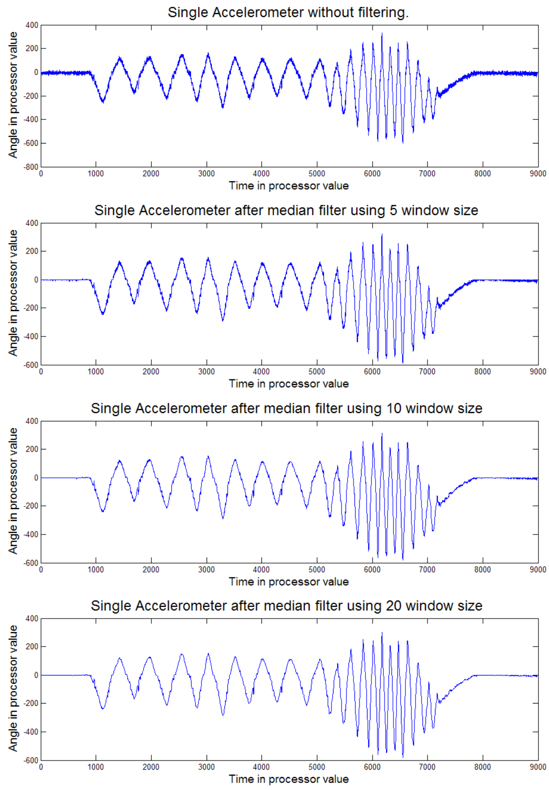

Fig. 3. Results of median filtering for the various window size(0,5,10,20).

2.2. EKF(Extended Kalman Filter)

EKF is described below in equation 1. EKF is consist of time update process and state update process iteratively, during these sequences, if the system is not deterministic, but noise is Gaussian distributed, then this algorithm can find local optimal solution(s).

Time update equation(predict)

$$\hat{x}_k^- = f(x_{k-1}, u_k, 0) \quad (1.a)$$

$$P_k^- = A_k P_{k-1} A_k^T + W_k Q_{k-1} W_k^T \quad (1.b)$$

Measurement update equation(correct)

$$K_k = P_k^- H_k^T (H_k P_k^- H_k^T + V_k R V_k^T)^{-1} \quad (1.c)$$

$$\hat{x}_k = x_k^- + K_k (z_k - H(x_k^-, 0)) \quad (1.d)$$

$$P_k = (I - K_k H_k) P_k^- \quad (1.e)$$

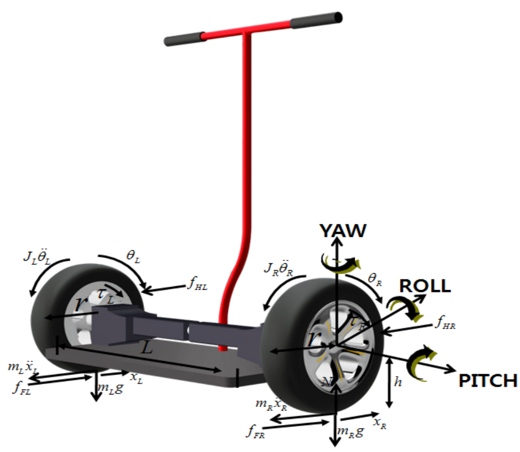

Figure. 4. Modeling of mobile inverted pendulum for EKF.

III. Experimental results

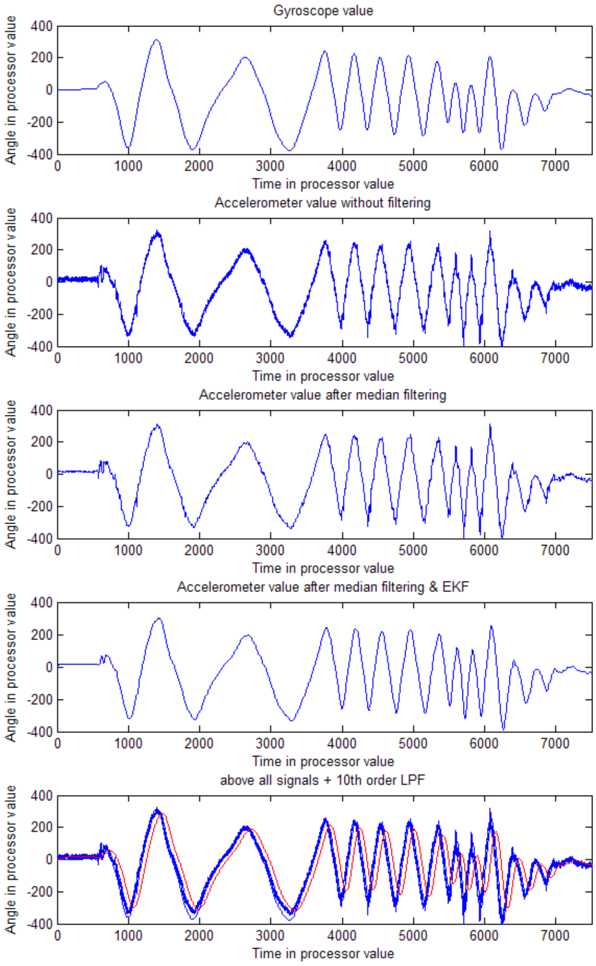

Fig. 5.a. Compensated gyroscope signal. Fig. 5.b. Accelerometer signal without filtering. Fig. 5.c. Accelerometer signal after median filter only(Window size = 20). Fig. 5.d. Accelerometer signal after median filter and EKF. Fig. 5.e. Above 4 signals and 10^{th} order LPF signal which have some time delay.

Figure 5 shows the experimental results for proposed algorithm and LPF. Figure 5.a. shows the compensated gyroscope signal. It's smooth and considered as reference when performance evaluation. Figure 5.b. shows raw accelerometer signal has many variation and weak for external disturbances. Figure 5.c. illustrates accelerometer signal after median filtering, high frequency, impulsive noise, is removed out. Figure 5.d. displays an accelerometer signal after median filter and EKF, which is similar with reference, compensated gyroscope signal. Figure 5.e. shows above 4 signals and LPF signal. Above 4 signal has almost same except for variation, but 10^{th} LPF signal(red line) has time delay caused by time constant.

IV. Performance evaluation

4.1. Spectrum analysis using PSD(Power Spectral Density)

In this paper, performance evaluation parameter is selected as spectrum analysis using FFT and PSD. Figure 6 illustrates the PSD of accelerometer signals applied various window size(0,5,10,20) of median filter.

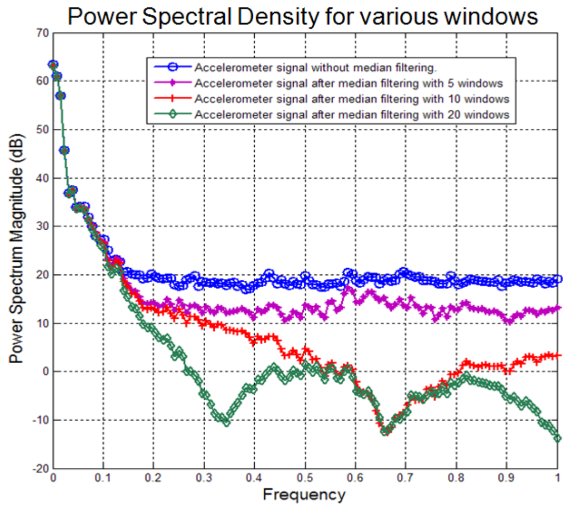

Figure 6. PSD of various window size of median filter.

4.2. Spectrum analysis using FFT(Fast Fourier Transform)

In figure 7, FFT signal of raw accelerometer signal, median filtered signal, and median filter and EKF signal are shown, respectively.

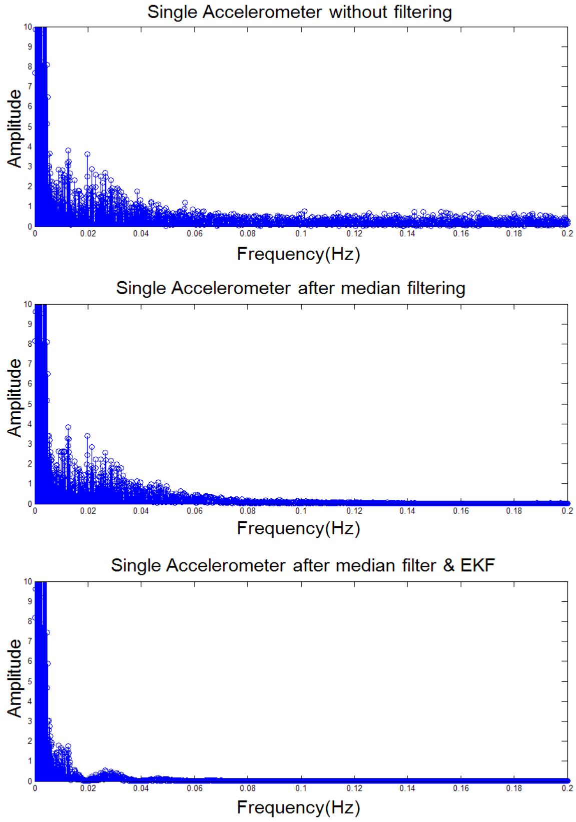

Fig. 7.a. FFT signal of without filtering. Fig. 7.b. FFT signal of median filtering with 20 window size. Fig. 7.c. FFT signal of median filter & EKF.

V. Simulation & Experiment

4.1. Mobile inverted pendulum block diagram

Conventional operating block diagram when using only PID controller is illustrated in figure 8.

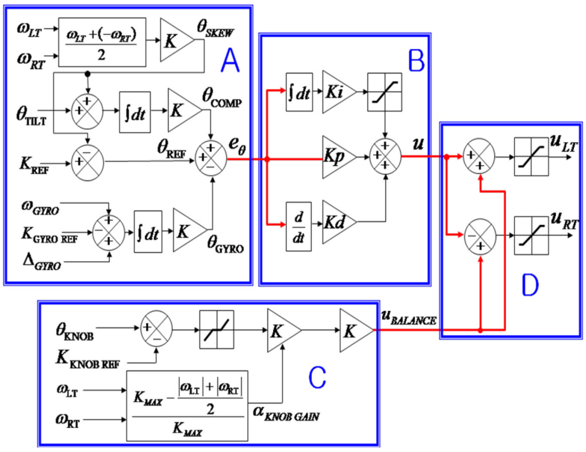

Fig. 8. Conventional operating algorithm of MIP.

A block of figure 8 is sensor fusion, between gyroscope and accelerometer, algorithm using 'kalman filter'. DC information of gyroscope signal is rejected and integrated to calculate gyroscope angle. And accelerometer is used for compensatin the accumulated drift error of gyroscope signal. In figure 10, proposed block diagram is shown. A-block is replaced with median filter and EKF.

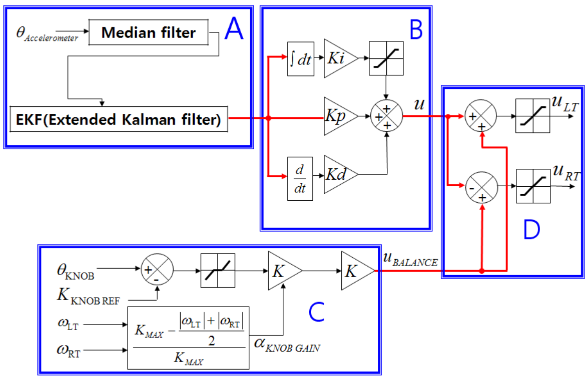

Fig. 9. Proposed operating algorithm of mobile inverted pendulum using single accelerometer.

VI. Conclusion

Conventional mobile inverted pendulum uses sensor fusion algorithm between multiple gyroscopes and accelerometers to calculate real-time angle. Single gyroscope control has accumulated drift error, and this cause divergence in future, as stated in section 2. And single accelerometer has a fatal shortcoming, weak for external disturbances. This paper proposed a new accelerometer filtering algorithm, median filter and EKF(Extended Kalman filter), and verify through simulations using matlab and real experiment. 'Segway' must cost reduce to be a next-generation transporter. For this aspect, single accelerometer filtering algorithm is essential for 'Segway'. Research on single accelerometer filtering algorithm for cost reduction and sensor fusion for performance improvement must be progressed concurrently. Future research topic on mobile inverted pendulum is, 1. Optimal controller design for a single accelerometer. 2. Study on predictive control method to reduce the response time and robust for the disturbances. 3. Cooperation control between mobile inverted pendulum and humanoid robot shown in figure 10, and so on. And performance evaluation method to be added is, Cross-correlation algorithm and RLMS(Recursive Least Mean Square) to calculate the difference between compensated gyroscope signal, as we think reference, and single accelerometer signal applied proposed algorithm.

Fig. 10. Cooperation control scheme between MIP and humanoid robot.

Acknowledgement

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